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# Proposal to Develop Imaging Hadron Calorimetry

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**Abstract**: This is a proposal to develop imaging hadron calorimetry for the planned Electron-Ion Collider – the EIC. At the EIC, individually identifying and measuring all particles in a jet of hadrons, using the detector subsystems providing the best energy/momentum resolution for each particle type, offers distinct advantages. Among these are a superior jet energy resolution and the best possible kinematic reconstruction of deep inelastic scattering events. This approach necessitates imaging calorimeters to distinguish energy deposits associated to either charged or neutral particles. The proposed work is based on initial studies performed with the DHCAL (Digital Hadron Calorimeter) prototype and includes studies which are essential to turn a validated concept into a mature technology. This is a new proposal.

## 1. Introduction

In recent years particle physics has seen a trend towards imaging calorimetry, i.e. calorimeters with very fine segmentation of the readout. The advantages of imaging calorimetry are many: application of Particle Flow Algorithms (PFAs) to the reconstruction of hadronic jets, improved single particle energy resolution through application of software compensation, equalization of the response with depth in the calorimeter, and last, but not least, improved charged particle (muon, hadron, electron) identification. The concept of imaging calorimeters has been proposed and developed foremost by the Linear Collider community and, in this context, by the CALICE collaboration [1]. However, recently all four major LHC experiments have either proposed or have initiated studies of imaging calorimetry for their high luminosity detector upgrades.

While the concept of imaging calorimetry has been shown to be beneficial for $e^+e^-$ collisions at center-of-mass energies up to 3 TeV [2], this approach is particularly suited for the environment of the planned Electron-Ion-Collider, the EIC. The relatively low collision energy, in the range of 10 to 146 GeV, produces hadronic jets where the particles impinging on the calorimeter are in general well separated. This results in an ideal condition for the application of PFAs. In this environment, the foremost challenge of PFAs, i.e. the identification of energy deposits in the calorimeter as belonging to charged or neutral particles, is not a major issue.

Imaging calorimeters for particle physics require fine granularity for both the electromagnetic calorimeters placed behind the central tracking device and the hadron calorimeter placed behind the electromagnetic calorimeter. The former is necessary to identify and measure photons, whereas the latter serves primarily to identify and measure energy deposits from neutral hadrons (neutrons and $K_L^0$.) In this context, we propose to develop imaging hadron calorimetry based on Resistive Plate Chambers (RPCs) [3] as active elements.

RPCs as active elements of an imaging calorimeter have been explored within the CALICE collaboration [1] by the DHCAL group. A large prototype calorimeter with approximately 500,000 readout channels has been built and was tested extensively in the Fermilab and CERN test beams [4-6]. The tests were very successful and can be regarded as validation of the technology. However, the DHCAL technology being novel, the tests also revealed certain shortcomings or areas where further developments are either necessary or desirable. Only with these additional studies can the DHCAL concept be turned into a mature technology and can be proposed for the hadron calorimeter of a future colliding beam detector. The shortcomings include, among others: the limited rate capability of RPCs, the difficulty in equalizing the response of RPCs, the distribution of high voltage to a large number of chambers, and the venting of the RPC gas mixture. We propose to address these issues within the context of this proposal. The proposed work is equally applicable to a detector destined for eRHIC or JLEIC.

## 2. Description of the DHCAL Technology

The Digital Hadron Calorimeter (DHCAL) used Resistive Plate Chambers [3] as active elements. The area of each RPC measured 32 × 96 $cm^2$. The chambers utilized the traditional two resistive-plate design with soda-lime glass as resistive plates [4]. The cathode and anode plates were 1.15 and 0.85 mm thick, respectively, and enclosed a single 1.15 mm thick gas gap. The chambers were flushed with a non-flammable mixture of three gases: tetrafluoroethane (94.5%), isobutane (5.0%) and sulfur hexafluoride (0.5%) and were operated in avalanche mode with a default high voltage of 6.3 kV. For other properties of the RPCs used in the DHCAL, in particular their rate capability for single minimum ionizing particles, see refs. [7, 8]. The rate capability for showering particles is typically inferior to the capability for single particles, but is more difficult to quantify, as it depends on both the absorber structure and the location of the chamber within the stack.

The readout boards each measured 32 × 48 cm$^2$, contained 1,536 1 × 1 cm$^2$ pads, and were placed on the anode side of the chambers. Two boards covered the area of one chamber. The readout boards contained two separate boards, a board featuring the pads and a board housing the front-end electronics, interconnected by dots of conductive glue. The electronic readout system was based on the DCAL III chip [9], which applied a single threshold to the signals from an array of 8 × 8 readout pads to define hits [5]. This type of electronic readout with single-bit resolution per channel is commonly referred to as 'digital'. The threshold discriminating the signals could be set individually for each chip, but was common to all 64 channels connected to a chip. The readout clock rate was 10 MHz. After receipt of an external trigger, hit patterns of the 64 channels connected to a chip were read out together with their corresponding time stamps in seven consecutive 100 ns time bins; one of these time bins occurred before the arrival of the particle in the stack. After receipt of an external trigger, hit patterns of the 64 channels connected to a chip were read out together with their corresponding time stamps in seven consecutive 100 ns time bins; one of these time bins occurred before the arrival of the particle in the stack.

The DHCAL layers were tested in absorber structures containing steel, tungsten or no additional absorber plates. Over the period of three years, the stacks were exposed to electron, pion, and muon beams and approximately 65 million events were collected. As an example, demonstrating the quality of the data and the simulation of the set-up, Fig. 1 shows the radial shower shapes, as measured with 6 GeV positrons.

## 3. Proposed studies

We propose to perform the four studies listed below. The purpose of these studies is to turn the DHCAL from a validated concept of an imaging hadron calorimeter into a mature technology to be proposed for the hadron calorimeter of an EIC detector.

### a) Long-term tests of fast RPCs

Typically RPCs can withstand particle rates of up to 100 Hz/cm$^2$ [7,8]. When subject to higher rates, the effective high voltage decreases leading to a loss of particle detection efficiency. The rate capability is directly linked to the conductance of the resistive plates utilized in the chamber, see Fig. 2.

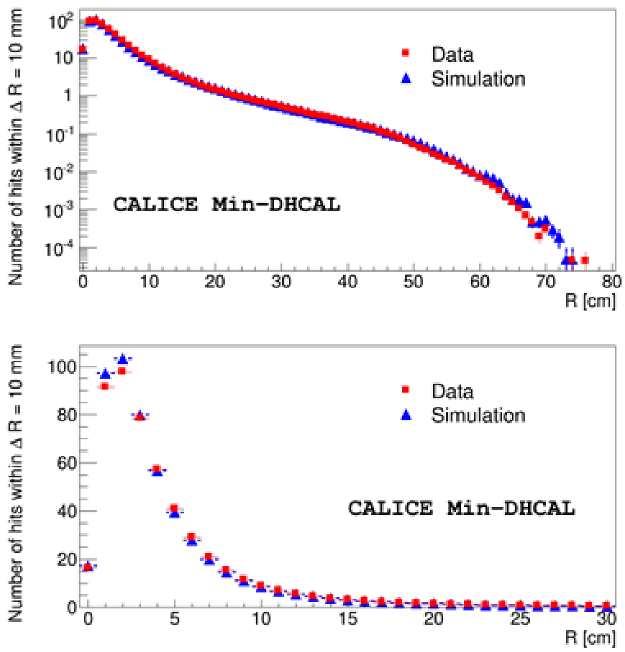


**Figure 1.** Distribution of the radial distance of hits from shower axis for 6 GeV positrons. The upper (lower) plot uses a logarithm (linear) y-scale. The areas of both plots are normalized to one event. The error bars include the statistical and systematic uncertainties for the data and statistical uncertainties only for the simulation.

Originally, the DHCAL technology was pursued for the hadron calorimeter of the International Linear Collider (the ILC), where the collision rates are expected to be extremely low. With the high projected luminosity of the EIC (several $10^{34}$ $cm^{-2}s^{-1}$) the particle rate in the forward region is expected to be of the order of kHz/$cm^2$ or higher, necessitating RPCs with improved rate capability.

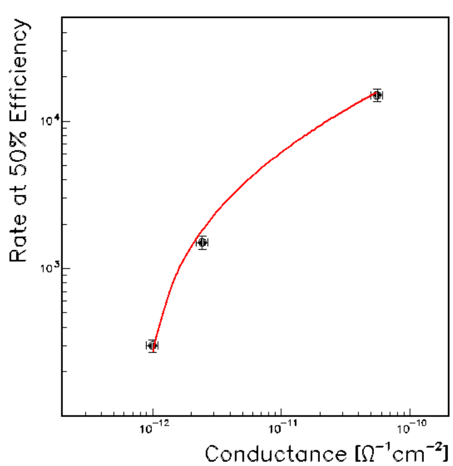


**Figure 2.** Rate at 50% efficiency versus conductance per area of the glass plates. The points were fitted to a polynomial of third degree. The result of the fit is shown as red line.

Together with COE College (Iowa), the DHCAL group developed semi-conductive glass with a bulk resistivity approximately two orders of magnitude lower than soda lime glass, the glass commonly used as resistive plates in RPCs. The group assembled two chambers with the new glass and subjected them to particles at the Fermilab test beam. The chambers showed the expected improvement in rate capability (the right most point in Fig.1). This improved rate capability appears to be sufficient for use as active elements of a hadron calorimeter in the EIC environment.

The next step in validating this new glass is to perform long-term tests. We propose to operate these chambers over the period of at least one year in a cosmic ray test stand. We will be monitoring the particle detection efficiency, the average pad multiplicity, the accidental noise rate, and the current through the chamber. If the prolonged application of high voltage (about 7 kV) leads to chemical or physical changes in the glass, such tests will reveal a degradation of the performance measures listed above.

In addition, we will perform an integrated charge test for the new glass material, by passing a constant current through the glass and monitoring the change of resistivity as a function of the integrated charge. This will determine if the glass material *dries out* with long-term high-rate operation.

### b) Long-term tests of 1-glass RPCs

To provide a stable response and to optimize the energy resolution of the calorimeter, the response of the individual RPCs in the stack needs to be equalized. The response is measured by the product of the efficiency and the average pad multiplicity for single minimum ionizing particles. In tests with the DHCAL prototype, the efficiency was measured to be sable and to be very high, around 93%. However, the pad multiplicity, averaged at 1.6 per single minimum ionizing particle, was seen to both vary significantly from chamber to chamber and to also change with time. This feature rendered the equalization procedure excruciatingly difficult.

The DHCAL group developed a novel design [10] of RPCs, which eliminated one of the two resistive plates of the traditional design. The gas volume in these new chambers is defined by the one glass plate and the anode plate with the readout pads. The novel design offers a number of distinct advantages: an average pad multiplicity close to one, see Fig. 3, a thinner chamber design, and a higher rate capability. The average pad multiplicity close to one significantly simplifies the equalization procedure. Again, two chambers were assembled based on the new design. The chambers were tested with cosmic rays and in the Fermilab test beam and performed as expected [10].

The next step in validating this new design is to perform long-term tests. We propose to operate these chambers over the period of at least one year in a cosmic ray test stand. We will be monitoring the particle detection efficiency, the average pad multiplicity, the accidental noise rate, and the current through the chamber. If the prolonged application of high voltage (about 7 kV) in the presence of the RPC gas leads to chemical or physical changes of the anode board, such tests will reveal a degradation of the performance measures listed above.

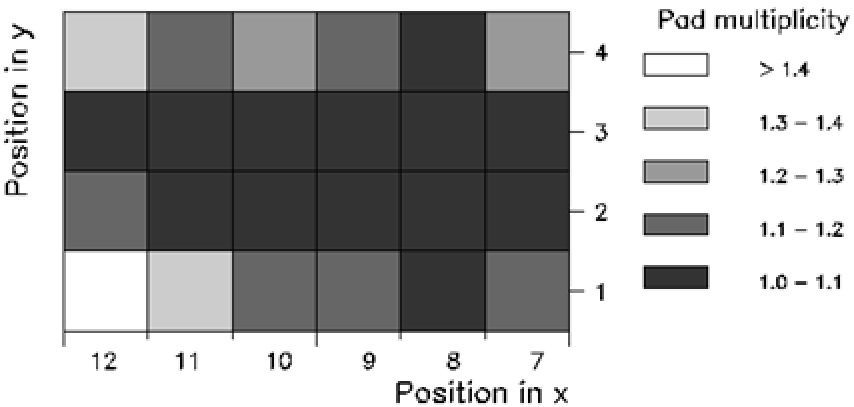


**Figure 3**. Average pad multiplicity measured for cosmic ray tracks as function of position on the 1-glass RPC.

### c) Development of a high voltage distribution system

At the EIC, a hadron calorimeter based on the DHCAL technology will contain of the order of 3,000 individual chambers, all operating under high voltage. For this large number of chambers a cost effective high distribution system is needed. The system is expected to provide the option to turn on/off individual chambers, to monitor both the voltage and the current of each chamber, and to fine-adjust the voltage within a range of say ±100 V.

The DHCAL group, and in particular University of Iowa, have started to develop such a system. A first prototype, capable of controlling a single channel was built and tested successfully. Unfortunately, due to lack of funding the effort came to a halt.

We propose to complete the work by a) implementing the monitoring of the voltage and current into the existing prototype of a distribution system, b) providing the capability of fine-adjusting the voltage, and c) to expand the system such that it controls up to 24 chambers. The proposed development is particularly challenging, as the chambers operate with high voltages in the range of 6 to 7 kV. To guarantee a stable operation, the transients when turning on/off individual channels need to be minimized.

### d) Development of a gas recycling system

The typical gas mixture used in RPCs is expensive and highly nocif for the environment. In the past, the refuse gas was simply vented into the atmosphere. New federal regulations are being drafted which will prohibit this irresponsible practice. IN the U.S. the new regulations are expected to become law within the next year or so.

In order to continue to operate RPCs (and not to violate federal regulations once in force), a gas recycling system needs to be deployed. The DHCAL group initiated the development of such a system, dubbed the 'Zero Pressure Containment' system. The challenge of the recycling system is to maintain a constant (atmospheric) pressure in the chambers, while capturing the gas. Figure 4 shows the current state of the system. The system was tested and performed very well, collecting all refuse gas while keeping a constant pressure on the output of the chambers. Again, due to lack of funding the project came to a halt.

**Figure 4.** Photograph of the prototype of a RPC-gas recycling system.

We propose to complete the development of a prototype gas recycling system. The next steps are a) the implementation of passive filters to purify the exhaust gas, and b) the long-term test with RPCs. The latter includes a comparison of the performance of RPCs supplied with virgin or recycled and purified gas.

## 4. Budget and effort

We request funding to support a postdoctoral appointee for one year, k$165. The postdoc will be working closely with the proponents of this proposal and will be located at Argonne National Laboratory. We also request a small amount of M&S funds ($10k) to cover the purchase of filters for the gas recycling system.

## 5. Summary

We believe that an EIC detector would greatly benefit from imaging calorimetry, improving in particular jet measurements and kinematic reconstruction. We propose to turn the DHCAL technology, which has been validated in extensive tests, into a mature technology by performing long-term tests of RPCs, by developing a high voltage distribution system, and by developing a gas recycling system.

## 6. References


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